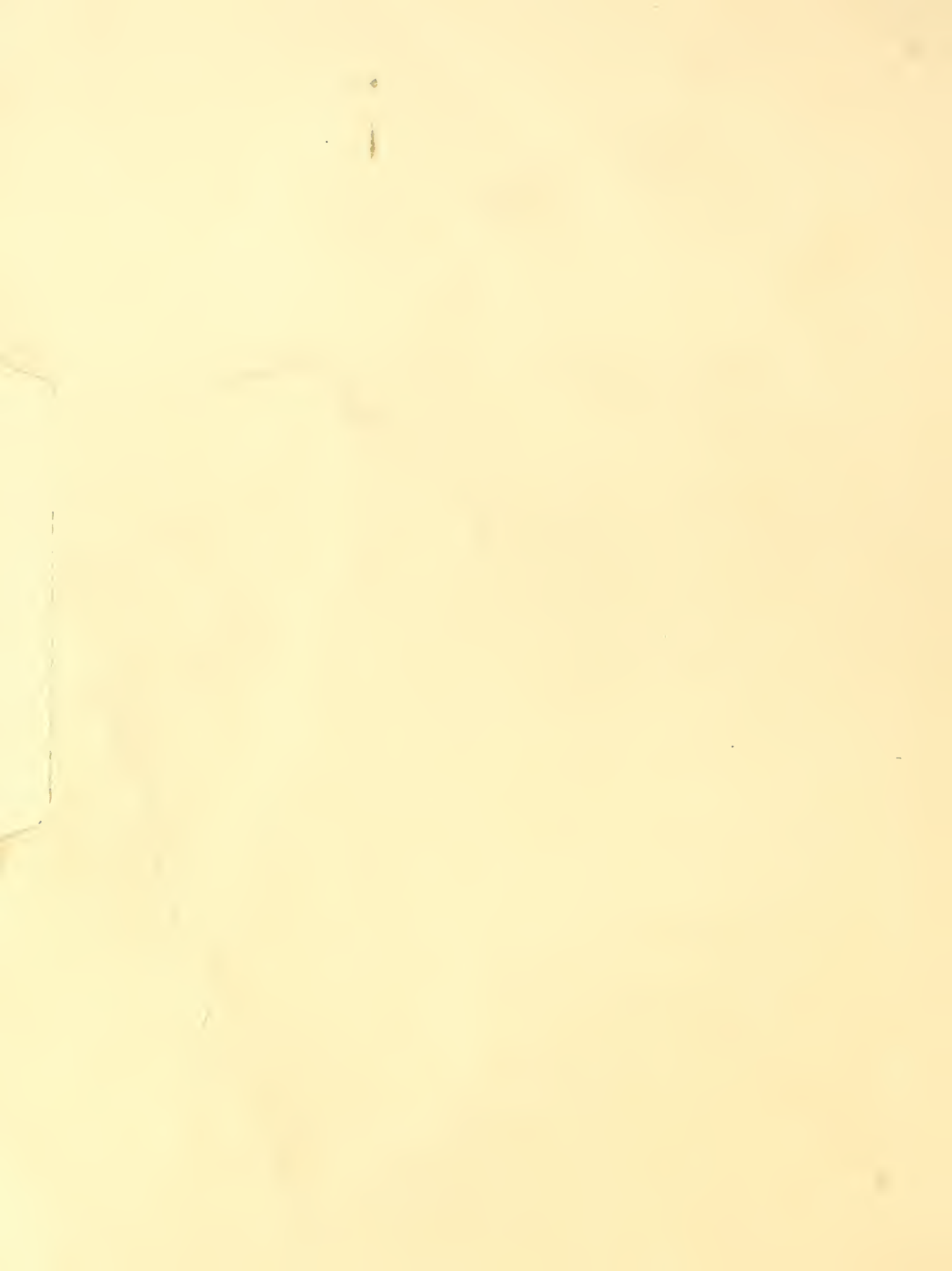


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# Combustion Recovery of Flaming Pine Needle Fuel Beds Sprayed With Water/MAP Mixtures

Aylmer D. Blakely

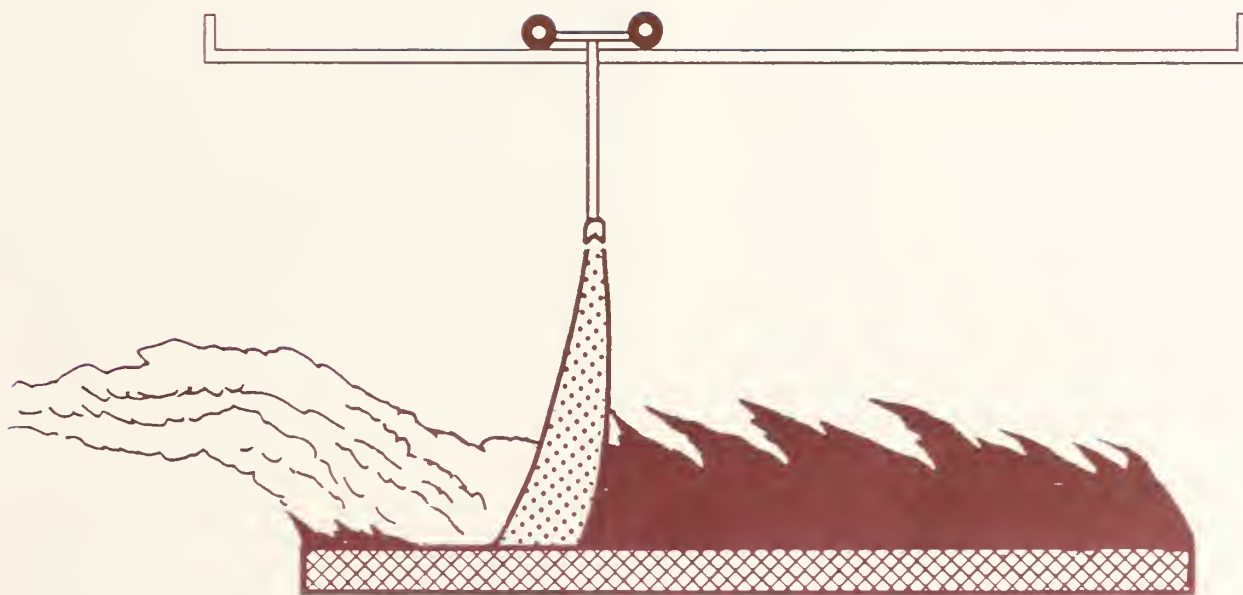
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## RESEARCH SUMMARY

The purpose of this study was to quantify the fire extinguishing capabilities of water with small amounts of mono-ammonium phosphate (MAP) added. Replicate fires were conducted to quantify the differences in energy release rates and durations before, during, and after treatments. In a wind tunnel with controlled environment 5 mi/h wind, 90 °F, 20 percent R.H.), ponderosa pine needle fuel beds were ignited, allowed to reach maximum energy release rate near 300 Btu/s, and five different amounts of water and water plus MAP were sprayed into the flaming beds. The consequent smoldering fuel beds were monitored for weight loss as the flaming combustion recurred, burned most of the available fuel, and then died out.

Weight loss traces were divided into segments and analyzed separately for reactions to different water and MAP applications. The segments were identified as BC, the "fire knockdown" capability of the application; SS1, the "holddown" capability; and SS2, the magnitude of the energy released and the time elapsed during maximum combustion recovery. Major differences in reactions to the different treatments were found between trace segments of individual fires, and these correlated well with reactions shown by the weight changes in trace segments of replicate fires.

Combustion recovery data from these fires show that water alone is the principal agent reducing flaming combustion to smoldering and that the chemical adds slightly to the reduction. Water reduced the energy release rates to which the fires recovered, but water plus chemical reduced the levels significantly more. The same was true for extending the time that the combustion stayed at the reduced energy release rates. The data in this study show a significant advantage in adding chemical retardant to water. The capability of water to immediately reduce flames to smoldering combustion was enhanced only slightly by retardant chemicals. But the chemical significantly reduced fire intensity and extended the times that flames were reduced as the smoldering continued beneath the surface of the burning fuel. Chemical retardant added to water can be a definite advantage during vegetation fire suppression efforts.

## THE AUTHOR

**AYLMER D. BLAKELY** received his B.S. degree in forestry in 1960 and his M.S. degree in forestry in 1970 from the University of Montana. In 1967, he joined the Intermountain Fire Sciences Laboratory in Missoula, MT, where he currently works in fire retardant chemical and delivery systems research in the Fire Suppression research work unit.

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# Combustion Recovery of Flaming Pine Needle Fuel Beds Sprayed With Water/MAP Mixtures

Aylmer D. Blakely

## INTRODUCTION

Forest fire retardants may be applied to wildfires from either air or ground tankers, but the majority of the approximately 30 million gallons (the volume varies by severity of the fire season) used each year is applied from airtankers. Less than 1 percent is applied by groundtankers. A Washington Office Policy Analysis Staff Report (Gale 1983) estimates that 30 percent of retardant delivered by airtankers is in direct attack to totally extinguish flaming combustion and stop the fire's advance. (This estimate may be low if the commonly used "half-on, half-off" tactic were included.) Two other reasons for using retardant are to cool the fire so firefighters or equipment can work closer to the fire and to slow the fire's advance until some other action can be taken. Indirect attack—placing retardant away from the active firefront—may be used if the fire is too intense and/or the terrain or fuels are not particularly conducive to direct attack.

Most currently approved retardants are long-term slurries that contain chemicals that are still effective even after the water has evaporated. Therefore, most retardant-effectiveness studies have been conducted with water/chemical mixtures that were sprayed onto fuels then allowed to dry before being ignited. Few studies have been made to quantify the fire-extinguishing abilities of currently used long-term fire retardant formulations that contain phosphates and sulfates of ammonia or other chemicals that inhibit combustion by altering fuel pyrolysis. No comprehensive laboratory studies under controlled conditions have been made to study the fire-extinguishing capabilities of thickened or unthickened water on mat-type fuel beds. Some studies have been made in uncontrolled conditions and others used overhead sprinklers to apply different retardants to lumber or boxes (Truax 1939; Grove and others 1962).

## Long-term Versus Short-term Retardants

Most fire specialists have long believed that long-term fire retardants are the most cost effective because the airtanker cost is the major part of the total delivery cost. But today costs per load of long-term retardant may approach the cost for airtanker delivery. It has therefore been suggested that costs can be reduced by delivering a cheaper retardant. The question arises, is a less expensive retardant cost effective? Can the cheaper retardant in forms such as plain water, thickened water, or foam,

retard fire and still significantly aid the firefighter, in some, if not all, situations. Use of the cheaper retardant in lower fire-intensity situations can save money. For example, suppose the difference in cost of long-term and short-term retardant were 35 cents per gallon. During a fire season when 30 million gallons were used, using the short-term retardant only 10 percent of the time would save more than \$1 million.

Some of the tradeoffs between short-term and long-term retardants are: (1) Acceptability—long-term chemical retardants may be unacceptable for use in municipal water sheds. (2) Color—persistent iron oxide pigments in some retardants are unacceptable in wilderness and residential areas. If not washed off immediately, fire retardant salts or pigments can ruin car paint and stain homes or scenic rock formations. (3) Effectiveness—what are the limits of effectiveness for various retardants under different fire/fuel situations, especially when the fire is under control (during mop-up or low fire-spread situations) or when the fire intensity is so high that retardant obviously will not be effective. (4) Application—if long-term retardants are to be used often in direct attack fire-extinguishing capabilities of new and different retardant formulations must be quantified. A more precise method is needed than just spraying retardant onto a burning pile of brush under ambient conditions and calculating how much retardant it takes to stop the flaming and smoldering, with no measurement of the amount of "overkill."

## Long-term Versus Short-term as Extinguishers

The purpose of the study reported here was to quantify the fire-extinguishing capabilities of water containing mono-ammonium phosphate (MAP), a commonly used chemical in forest fire retardants. The study method realistically tests actual retardant use because retardants usually retard combustion and seldom totally extinguish it, especially during the initial application. Ideally, a retardant would completely extinguish all flaming and glowing combustion. But many times the fire is only retarded or slowed, or fire intensity is decreased for only a short time. Knowing the effects of different amounts of water and chemicals in different fire and fuel situations is important in fire suppression efforts. Even though the fire's intensity level is decreased for only short periods, those times can be used by firefighters to get closer to the fire for more effective direct attack.



We need to answer questions like the following ones. Does water with chemicals knock down flame better than water alone? Which application causes the energy release rate to be reduced for the longest time? On what fuels and fire intensities can the water or chemicals do the required job (be effective)—not necessarily extinguish, but lower the fireline intensity for a period during which some other fire-stopping action can take place? This goes along with the idea of “retardant.” Can water (short-term retardant) be substituted for water plus retardant (long-term retardant) with satisfactory results? If so, in what situations? Is there a significant advantage to using long-term retardant formulations to *extinguish* fire, and is it cost effective compared to water alone or with thickeners added?

Plain water is commonly used to extinguish fire because it is readily available, and it can be effective in the right circumstances. When water is plentiful and readily available, chemicals are seldom added except in some special situations such as aircraft fires where water alone has limited effectiveness. In situations where water is scarce and must be used judiciously, such as aircraft delivery on wildfires, additives are commonly used to increase effectiveness. Fire extinguishers containing only dry chemicals are commonly used for structural and other “inside” fires with high success unless the volume of the extinguisher is too small for the quantity of burning material. The extinguisher usually contains chemicals that smother burning materials and/or decrease the flammability of evolved gases rather than just absorbing heat energy. Ironically, few if any common extinguishers contain only water.

The least use of additives seems to be in water dispersed from ground tankers. The reasons are often: (1) the lack of specialized equipment to mix and pump water plus additives; (2) the adverse effects of the chemical residue on salvageable items remaining after the fire; (3) the logistics of applying water plus additives; and (4) the cost (Pickett 1975). Of these reasons, the lack of proper equipment is the most important deterrent to use of additives. Often the advantages in reducing fire intensity are overlooked, and firefighters have not been properly trained or are unaware of the advantages of water additives.

## How Fire Is Extinguished

Water extinguishes fire as follows: (1) by reducing the oxygen supply; (2) by cooling to temperatures below that required to ignite unburned fuel particles and sustain combustion; (3) by diluting flammable gases to a concentration at which they will not ignite; (4) by chemically altering pyrolysis of rapidly heating fuels enough to change the composition and flammability of evolved gases and vapors; and (5) combinations of all of the above actions. When water is applied to burning forest fuels, a combination of all of these actions occurs. We generally think of cooling and smothering as the most effective. But what happens when water is applied in too small a quantity or in a form that limits its availability to alter combustion? For example, when a straight stream of water is sprayed into the flames, the water contacts the fuels in a small area. That area may be extinguished while the water is being directed at it. But when the water stream is

removed, the surrounding flames quickly evaporate the water and the area will flame again unless all the adjacent fuels have also been cooled enough to prevent heat transfer or there is chemical present to retard combustion.

In wildland fires the main purpose of water is to cool the combustion to a point that the fire will not sustain itself. On indoor structures an important method of extinguishment is to fill a room with the right amount of water in a spray form so that the room is filled with steam that both cools and smothers the flames and dilutes the flammable gases and vapors (Royer 1952). The same principle can be used for open wildland fires, but not nearly as effectively, because the steam cannot be confined in an effective volume. Therefore we find that water is effective in a straight stream form, but is not as effective as a mist or steam would be for cooling, smothering, and diluting.

## Previous Retardant Testing

Many tests have been performed to determine the advantages of adding chemicals to water for extinguishing fires. In the late 1930's Truax (1939) showed that several chemicals would improve the effectiveness of water to stop flaming and glowing combustion on burning fires in beds of leaves and needles. Truax showed that the added chemicals helped to prevent rekindling, but he concluded that if plenty of water was available the addition of chemicals did not improve the effectiveness of water enough to warrant the additional logistical effort and expense. A USDA Forest Service report (1955) showed that energy release was decreased when water solutions of ammonium sulfate and ammonium phosphate were applied to burning piles of brush. Studies done with additives (Groves 1962) showed that they could increase the extinguishing effect of water. Thickeners, foams, retardant chemicals, surfactants, and reflectors all increased the effectiveness of water. But evidently the increased effectiveness of additives shown by these studies did not convince firefighters that the advantages would surpass the disadvantages caused by extra needed equipment and logistics when using additives in ground engines and pumpers. Therefore, the use of additives has not become prevalent among wildland or structural engine crews. Recently, much interest has been shown in the use of small amounts of chemicals that can be added to water to produce different qualities of foam for different firefighting situations. These foams are designed to cool and smother flames, and they require a minimum of extra equipment and effort to apply.

Blakely (1985) introduced a laboratory method for quantifying the fire-extinguishing capabilities of water alone and water with added thickeners and chemical fire retardants. The objective of the study was to develop a method for quantifying differences between the fire extinguishing capabilities of water with and without fire retardant chemicals, and with or without thickening agents. The study identified water as the principal cooling agent for knocking down (KD) flaming combustion. Adding retardant chemicals improved the flame KD capabilities of water very little, but the increased viscosity and added retardant salt did minimize the measured fire intensities. The report discussed only eight fires that were conducted

to demonstrate the feasibility of using the new method for evaluating and studying the extinguishment capabilities of fire retardants.

## METHODS

The previous study by Blakely (1985) used "combustion recovery" to examine the effects of water alone and water combined with thickening agents and/or fire retarding chemicals on flaming and smoldering combustion. The concept of combustion recovery examines the consequences when retardant quantity is insufficient to knock down the flames and absorb all the energy being released by the burning fuel. Smoldering continues in the untreated fuels beneath the treated fuels. The heat from below evaporates the water and rapid combustion (flaming) starts again. The time required for flaming to recur and the level of energy release depend on the water and chemicals that are protecting the fuel from the heat source beneath the upper layers.

Fuel is less available to burn when coated with water or chemicals that prevent heat absorption or the coating causes fuel to burn at an intensity too low to ignite the adjacent fuel elements. Theoretically, if the retardant or water protects a fuel element and does not allow ignition before the contributing heat source has burned itself out, or if the energy release rate ( $E_R$ ) is too low to transfer ignition energy to the next element, then the fire will not sustain itself. In most cases it is not a single fuel element that contributes to ignition but rather the total heat energy that each element receives from the entire mass that is burning.

For this study, beds made of 4 pounds of untreated ponderosa pine needles were surface ignited along the edges and middle and allowed to become fully involved and reach maximum  $E_R$  before treatment was started. (Irradiance proportional to  $E_R$  was measured with a Gier-Dunkel radiometer.) The fire intensity of untreated fuel increased to maximum output in about 20 seconds, when the treatment was started. The retardant was sprayed in a fan-shaped pattern directly into the flames from an overhead nozzle that was moved upwind along the bed at a speed set by the predetermined amount of treatment. Different amounts of retardant were applied to replicate fires with similar pretreatment burning rates. After application, beds were allowed to burn down to a minimum  $E_R$  and then allowed to recover to a maximum, subject to the fuel quantity remaining and the effectiveness of the treatment. During the burn, weight loss and radiation energy emitted from the fuel bed and flame plume were recorded on a micro computer and monitored for about 12 minutes after the end of retardant application. Weight loss and irradiation traces and weight/time data taken from the traces are listed in the appendixes. The experimental burns were conducted in a controlled-environment wind tunnel in a 5 mi/h wind at 90 °F free air temperature and 20 percent relative humidity.

During the 1985 study, insufficient data were gathered to present a statistical analysis of the various effects. The study reported here included several more experimental burns that are used in an analysis that shows correlations

of retardant amounts to reductions in energy release rates and durations. The previous study showed that thickening agents, retardant chemical concentrations, and total amounts of water had measurable effects on the energy release rates. This study does not examine the effects of thickening agents but only the effects of water alone and water combined with mono-ammonium phosphate (MAP).

Five different amounts of water were applied to burning fuels: 144, 216, 288, 360, and 432 g. There were four replicates of the 144-g application and three replicates of each of the others. In addition, two replicates each of 144, 288, and 432 g water with 24 g mono-ammonium phosphate added were applied to burning needles. The solution percentages (on a weight/weight basis) were 14.3, 7.7, and 5.3, respectively. The amount of MAP was held constant to examine the effect of equal amounts of chemical distributed into the fuel bed by different amounts of water. Volumes of liquid converted to gallons per 100 square feet (gpc) are: 144 g = 0.32 gpc; 288 g = 0.64 gpc; and 432 g = 0.95 gpc.

## Experimental Methods for Measuring Combustion Recovery $E_R$

The methods used in this study are similar to those used in the Blakely (1985) study but with some improvements in data acquisition and recording equipment and data analysis techniques. The system for measuring weight loss was changed to a more accurate balance, with greater sensitivity to rapid weight changes. The same radiometer was used, but it was positioned to view all of the combustion zone and record the irradiation so that it could be used to more precisely detect changes in the fuel bed weight loss. In the previous study, the radiometer trace was used only for determining the point of maximum  $E_R$  when the sprayer was turned on.

The weight loss traces were analyzed electronically and with computer software to convert to Btu's and Btu/s. (Previous laboratory studies [George and Blakely 1970] have shown that ponderosa pine needles have a heat of combustion of 8,745 Btu/lb). The computer program calculated the  $E_R$  by averaging fuel bed weights along segments of the traces that showed constant weight loss (steady state or SS). Trace segments were determined by examining the irradiation trace for high and low  $E_R$  points (described below). These points were designated where major changes occurred in the fire intensity. The time points were picked from the irradiation trace rather than from the weight trace because the changes were more obvious and easier to locate on the irradiation trace.

The maximum pretreatment  $E_R$  (Btu/s) for each fire (occurring soon after ignition) was compared to  $E_R$  that occurred as the fire recovered from the different treatments. For each of the weight loss segments described below, a reduction percentage was calculated. The percentages were used for comparisons rather than just Btu/s because of slight differences in the pretreatment  $E_R$  for each test fire. The length of time (duration) each fire burned at the different posttreatment steady state  $E_R$  was measured and used as another parameter for determining effectiveness. Each set of data was fitted by a least squares method; the plotted data and equations are in the appendixes.



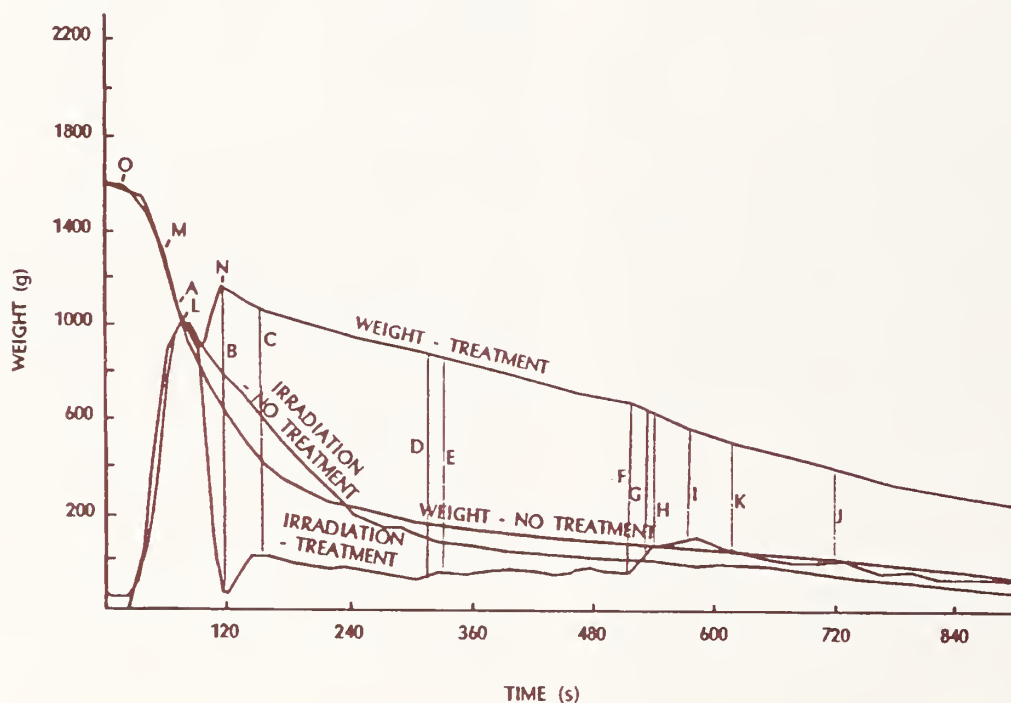
## Combustion Recovery Phases of Fires

**Trace Segment B to C**—The energy release recorded immediately after sprayer shutoff is the segment of the weight loss trace from B to C (fig. 1). This segment describes the  $E_R$  that is affected by both the water and the chemical. It is the segment that best indicates the fire "knock-down" (KD) abilities of the retardant. The duration of B to C is short (usually less than 15 seconds) compared to the other steady-state  $E_R$  segments; therefore the average  $E_R$  was measured for only a few seconds immediately after treatment shutoff.

The KD parameter, not used in the 1985 study, was detected in the current study, when the radiometer was repositioned and more sensitive weight loss equipment

was used. KD was first noticed as glowing combustion at the upwind end of the burning fuel bed. Under close examination, a steep segment was found on the weight loss trace and a corresponding rapid increase on the irradiation trace for a short period that quickly decreased and became the first steady-state burn trace (SS1). The KD parameter was first considered to be part of the SS1 energy release, but when examined separately its  $E_R$  was found to be sensitive to amount and type of treatment that was being applied to the burning fuel.

**First Steady-State Segment (SS1)**—Immediately after treatment shutoff and KD, the weight loss rate decreased slightly and began an extended steady state (SS1). SS1 was a period when the maximum amount of retardant was on the fuel and the energy release was at



**Figure 1**—Points on the weight loss and irradiation curves that correspond to major changes in energy release rate caused by application of retardant, evaporation of water, and effects of chemical application. Displays traces for a 432-g application of water plus MAP.

A-K: times taken from irradiation trace

L-O: times and weight traces taken from weight trace

A: maximum energy release

B: lowest  $E_R$  on irradiation trace immediately after treatment

C: beginning of fire effects after retardant application and start of SS1

D: minimum  $E_R$  during SS1

E: short  $E_R$  increase during SS1

F: low energy output point where fire starts to recover to maximum  $E_R$ —corresponds to start of SS2

G:  $E_R$  is back to same level as at start of SS1

H: SS2  $E_R$  begins to fall

I: combustion recovery reaches it's maximum

J: end of SS2— $E_R$  begins steady decrease until fire is out

K:  $E_R$  recovers to same level as at the start of SS1

L: time when the treatment starts

M: point 10 seconds before treatment starts—used for calculating maximum energy release before treatment

N: time when treatment stops

O: weight of fuel bed before ignition



a minimum. During this period, most of the water was being driven off so duration was directly related to the amount of water applied. The flaming combustion had been knocked down so that there was only smoldering combustion beneath the surface. The smoldering combustion produced sufficient heat to continue drying the treated fuels and sustain itself until enough heat was generated for flames to reappear. At that point, the total energy release of the fuel bed began to accelerate and recover (SS2).

The first steady-state period was followed by a second steady-state period (SS2) that reached a higher weight loss rate with increased flaming. The two steady-state periods varied in  $E_R$  and duration, corresponding to the total amount of water and other chemicals applied. The effectiveness of the retardant applications was determined by comparing the magnitude and duration of weight loss rates.

**Second Steady-State Segment (SS2)**—SS2 started as SS1 ended, but the  $E_R$  calculation was started after the weight loss rate became constant. By the time SS2 started, most of the water had evaporated, and some of the retardant chemical still remained on the fuel. During SS2 the  $E_R$  reached its highest magnitude since the retardant was applied, but the intensity never equaled the pretreatment rate because during SS1 most of the upper fuel layers burned away and the total fuel loading was reduced.

**$E_R$  Duration Measurement**—Elapsed time (duration) was measured so fire's reactions to water and/or chemical could be determined and compared. Duration was the time  $E_R$  stayed at a level that sustained combustion under the existing conditions. When retardant was on the fuels, the  $E_R$  was at a steady state much below the pretreatment  $E_R$ . Duration was a function of  $E_R$ . When the treated fuel was burning, it was the treatment that controlled the duration by limiting the available fuel and thereby controlling the  $E_R$ .

## RESULTS AND DISCUSSION

During untreated control burns, the burning rate of fuel accelerated rapidly to a maximum, held there momentarily, then decreased at a much slower rate until the combustion stopped (fig. 1). For extinguishment tests, when the irradiation trace reached its highest point, water or water plus MAP was applied to the flames of burning fuel beds. None of the applications completely stopped combustion; therefore sufficient heat remained to allow combustion recovery. The extent of recovery depended on the amount of water and/or chemical present on the fuel that could retard the combustion by heat absorption, cooling, alteration of flammable products, and so on.

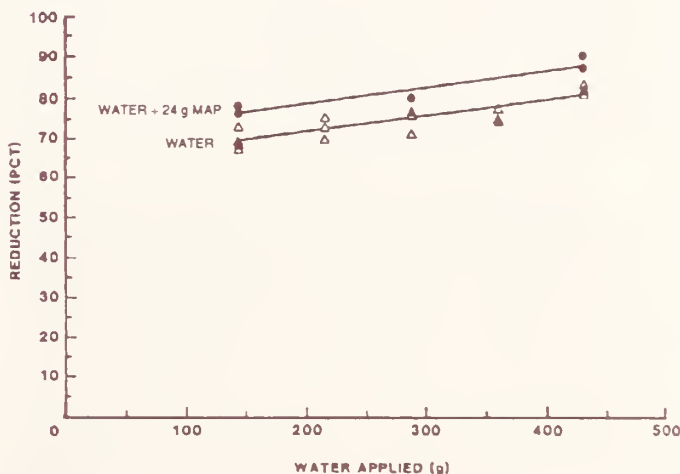
### Weight Loss Trace Segments BC, SS1, and SS2

Several different methods were used to describe what happened when water with or without chemicals was sprayed into the flaming fuel bed. The weight loss and irradiation traces were analyzed to define the time points and trace segments when burning rates changed.  $E_R$  was

determined from the different segments of weight loss traces then plotted in Btu/s or as a fraction of the maximum untreated fuel  $E_R$ . The segment duration times were plotted in minutes or as a fraction of duration of other trace segments.

Several trace segments identify the fire's reaction to retardant, but the most useful line segments are B to C, C to F (the first steady state [SS1]), and F to J (the second steady state [SS2]). B to C is a measure of the flame knockdown (KD) capability of the retardant; SS1 is a measure of the holddown capabilities of the retardant; and SS2 shows the level of the fire intensity as the fire recovers to the maximum attainable with the remaining fuel, water, and/or retardant chemical still present. SS2  $E_R$  is a sustained level for several seconds or minutes. The  $E_R$  at I, the point when the maximum combustion recovery occurred, was calculated by averaging the weight loss for 3 seconds on each side of I. The time for the fire to recover to that level was measured between point B and I (BI).

**BC Energy Release Rate**—The rate of weight loss for 10 seconds immediately after the application stopped (segment B to C) determined the  $E_R$  that occurred as retardant was sprayed into the flames and fuel. This  $E_R$  was much lower than the pretreatment burning rate and higher than the SS1 rate. It lasted for only the few seconds before the  $E_R$  subsided to a steady state. Figure 2 and table 1 show the relation of amount of water applied to the fuel bed vs. the reduction in  $E_R$  shown as a percentage of the pretreatment  $E_R$  immediately before retardant application. The  $E_R$  was reduced as expected with each increase in the amount of water applied. The addition of MAP caused an additional reduction in  $E_R$  of from 6.8 to 7.2 percent, with the highest reduction at the lowest chemical concentration and the most water applied. Figure 2 shows that spraying 144 g water to the burning fuel bed reduced the  $E_R$  by 69.5 percent. When 24 g MAP was added to the 144 g water (14.3 percent solution) and applied to the burning beds, the  $E_R$  was reduced another 6.8 percent over plain water. Three times as much water reduced  $E_R$  by 80.9 percent and adding MAP reduced the  $E_R$  another 7.2 percent.



**Figure 2**—BC (knockdown)—reduction of energy release rate for water, and for water plus MAP.

Table 1—BC energy release rate data

Fire	Water	MAP	BC	BC reduction	Pretreatment $E_R$
	---- g ----		Btu/s	Percent	Btu/s
M28N1	144	0	72.3	72.9	267
M28N2	144	0	86.7	67.6	268
M28N3	144	0	75.2	69.4	246
M28N4	144	0	86.7	68.7	277
JUN11N2	144	24	55.9	77.6	249
JUN11N3	144	24	54.0	76.4	229
JUN8N1	216	0	77.1	72.7	282
JUN8N2	216	0	61.7	75.1	248
JUN8N3	216	0	73.2	69.8	242
JUN9N1	288	0	71.3	71.3	248
JUN9N2	288	0	61.7	76.5	262
JUN9N3	288	0	55.9	75.9	232
JUN11N4	288	24	46.3	80.1	233
JUN11N5	288	24	46.3	80.2	234
JUN9N4	360	0	55.9	74.6	220
JUN9N5	360	0	55.9	77.7	251
JUN9N6	360	0	61.0	75.4	248
JUN4N1	432	0	44.3	83.5	269
JUN4N2A	432	0	42.4	82.5	242
JUN10N1	432	0	48.2	81.3	258
JUN11N6	432	24	25.1	90.7	271
JUN11N7	432	24	30.8	87.4	245

Table 2—SS1 energy release rate data

Fire	Water	MAP	SS1	SS1 duration	SS1 start	SS1 reduction
	---- g ----		Btu/s	---- min ----		Percent
M28N1	144	0	52.5	0.30	0.12	80.3
M28N2	144	0	62.4	.63	.17	76.7
M28N3	144	0	60.2	.53	.47	75.5
M28N4	144	0	60.6	.70	.10	78.1
JUN11N2	144	24	13.7	2.13	.90	94.5
JUN11N3	144	24	25.1	2.47	.32	89.0
JUN8N1	216	0	29.6	1.83	.50	89.5
JUN8N2	216	0	24.3	1.60	.43	90.2
JUN8N3	216	0	24.0	1.50	.58	90.1
JUN9N1	288	0	25.6	1.93	.77	89.7
JUN9N2	288	0	33.0	1.60	.63	87.4
JUN9N3	288	0	22.7	2.60	.68	90.2
JUN11N4	288	24	22.9	5.00	.72	90.2
JUN11N5	288	24	16.4	4.67	.95	93.0
JUN9N4	360	0	23.8	3.33	.90	89.2
JUN9N5	360	0	25.8	5.33	.75	89.7
JUN9N6	360	0	28.6	5.53	.58	88.5
JUN4N1	432	0	17.7	5.13	.98	93.4
JUN4N2A	432	0	21.5	5.93	.63	91.1
JUN10N1	432	0	21.6	4.27	.67	91.6
JUN11N6	432	24	12.5	8.50	3.68	95.4
JUN11N7	432	24	14.8	7.40	2.95	94.0

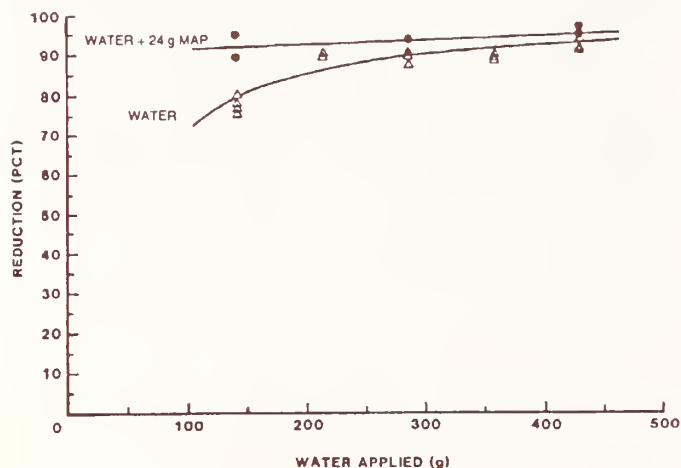


Figure 3—SS1 (holddown)—reduction in energy release rate for water, and for water plus MAP.

**SS1 Energy Release Rate**—Data for SS1 are shown in table 2 and figure 3, and also in appendix C. By spraying 144 g water, the pretreatment  $E_R$  was reduced by 79.1 percent. By adding 24 g of MAP to 144 g water, the  $E_R$  was reduced by 91.4 percent, slightly more than the reduction caused by doubling the water (288 g) with no chemical. Clearly, the first 144 g of water had the most effect; each additional 72 g added to the effect but by a much reduced amount. Tripling the water reduced the  $E_R$  92.4 percent and adding 24 g MAP to the water reduced  $E_R$  only another 1.7 percent.

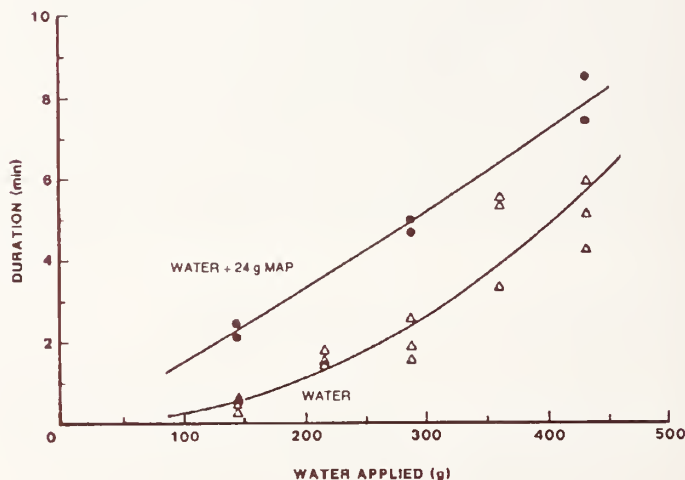


Figure 4—SS1 (duration of holddown) for water, and for water plus MAP.

Figure 4 shows the effects of water alone and water with MAP on the duration of SS1. When 144 g water is applied, the SS1  $E_R$  is held to a minimum for 0.56 minutes before it starts to recover and flame again. By adding 24 g MAP to the water, the holddown time is extended almost fourfold as long as water alone. Doubling the water treatment to 288 g increases the holddown period fivefold the duration with 144 g treatment, and tripling the water increases the duration tenfold. Adding 24 g MAP to 432 g water extended the duration of the SS1  $E_R$  to just under 1½-fold.

Table 3—SS2 energy release rate data

Fire	Water	MAP	SS2	SS2 duration	SS2 start	SS2 reduction
	---- g ----		Btu/s	---- min ----		Percent
M28N1	144	0	96.4	0.70	0.82	63.9
M28N2	144	0	96.9	.60	.90	63.8
M28N3	144	0	82.8	1.07	1.07	66.3
M28N4	144	0	90.2	0.93	1.07	67.4
JUN11N2	144	24	47.7	1.33	3.77	80.8
JUN11N3	144	24	36.6	3.40	3.08	84.0
JUN8N1	216	0	66.1	1.43	2.95	76.6
JUN8N2	216	0	69.2	1.67	2.92	72.1
JUN8N3	216	0	54.6	1.50	2.50	77.4
JUN9N1	288	0	44.5	1.30	4.17	82.1
JUN9N2	288	0	46.2	1.60	2.35	82.4
JUN9N3	288	0	49.5	1.67	4.90	78.7
JUN11N4	288	24	21.4	3.83	6.00	90.8
JUN11N5	288	24	28.2	2.27	6.53	87.9
JUN9N4	360	0	32.2	3.03	4.65	85.4
JUN9N5	360	0	80.4	.87	7.15	68.0
JUN9N6	360	0	55.3	1.67	6.57	77.7
JUN4N1	432	0	26.1	5.10	7.40	90.3
JUN4N2A	432	0	25.6	3.47	6.90	89.4
JUN10N1	432	0	38.9	3.57	5.33	84.9
JUN11N6	432	24	14.2	3.33	12.18	94.8
JUN11N7	432	24	16.1	5.00	10.42	93.4

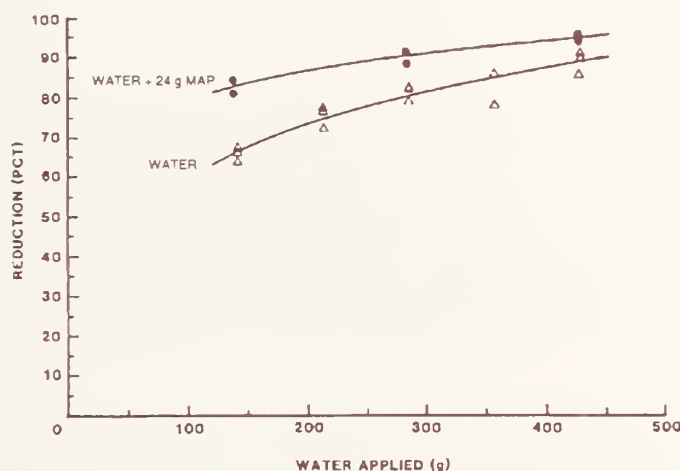


Figure 5—SS2 (combustion recovery)—reduction in energy release rate for water, and for water plus MAP.

**SS2 Energy Release Rate**—SS2 energy release data for individual fires are shown in table 3 and figure 5, and also in appendix C. The SS1  $E_R$  (144-g water application) increased by 16.4 percent after 0.56 minutes, the beginning of SS2  $E_R$ , and continued at that rate for 0.92 minutes before slowly decreasing in intensity until all combustion stopped. Adding 24 g MAP to 144 g water reduced the SS2  $E_R$  82.3 percent. Doubling the water (without MAP) reduced the SS2  $E_R$  by 79.8 percent; adding 24 g MAP to the water reduced  $E_R$  an additional 9.8 percent. Tripling the water (432 g) reduced the  $E_R$  by 87.9 percent and adding 24 g MAP reduced  $E_R$  another 6.0 percent.

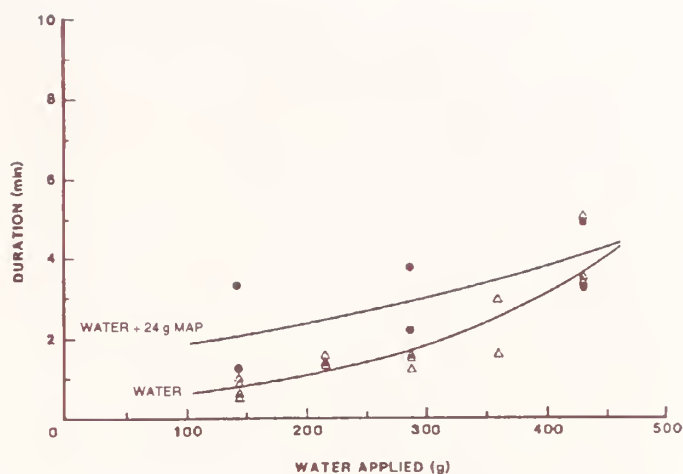


Figure 6—SS2 (duration of combustion recovery) for water, and for water plus MAP.

Figure 6 plots the duration of energy release rate during the recovery to maximum intensity, which was lower than in the untreated fuel. It shows the effects of water alone and water plus MAP on the duration of SS2. As the amount of water/MAP is increased, the duration increases corresponding to a decrease in the intensity of the burning fuel. When 144 g water was applied to the burning fuels, SS2  $E_R$  remained constant for 0.85 minutes. Adding 24 g MAP to the water increased the time to 2.32 minutes, almost threefold. Doubling the water treatment doubled the duration to 1.76 minutes. Adding MAP less than doubled the duration. Tripling the water to 432 g increased the duration to 3.67 minutes; adding 24 g MAP extended the duration only 0.35 minutes. The addition of MAP extended the duration for water, but not to the extent of a larger volume of water, and MAP was less effective at lower concentrations.

**Combustion Recovery**—Figure 7 plots the time from when the sprayer was turned off until the onset of combustion recovery. Point F (fig. 1) was actually the end of SS1 and the beginning of SS2. The duration indicates the effect of water and chemical on the combustion recovery time. Table 3 lists the treatments and their effects on the time required for the fire to evaporate the water and start to recover to an  $E_R$  magnitude, which was controlled by the fuel volume, water, and chemical remaining in and on the fuel when SS1 ended. When 144 g of water was sprayed, 1.12 minutes elapsed before evaporation was sufficient to allow the fire to begin to recover from the lowest  $E_R$ . When the treatment was doubled, the time increased to 4.06 minutes, almost fourfold; and when tripled to 432 g water, the time was extended to over sixfold. The addition of 24 g MAP to the water almost tripled the time delay at the 144 g treatment level, and caused a 72 percent increase when the treatment was doubled and 56 percent increase when it was tripled. The addition of MAP to water had progressively less effect in delaying combustion recovery as the water volume increased and the solution percentage decreased.



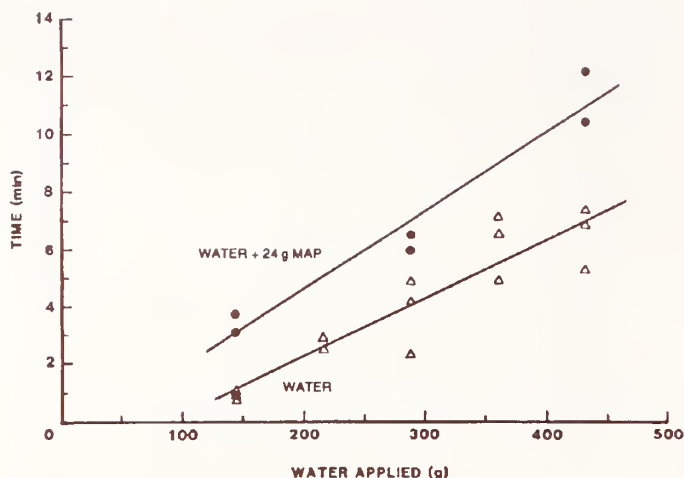


Figure 7—Time to start of combustion recovery for water, and for water plus MAP.

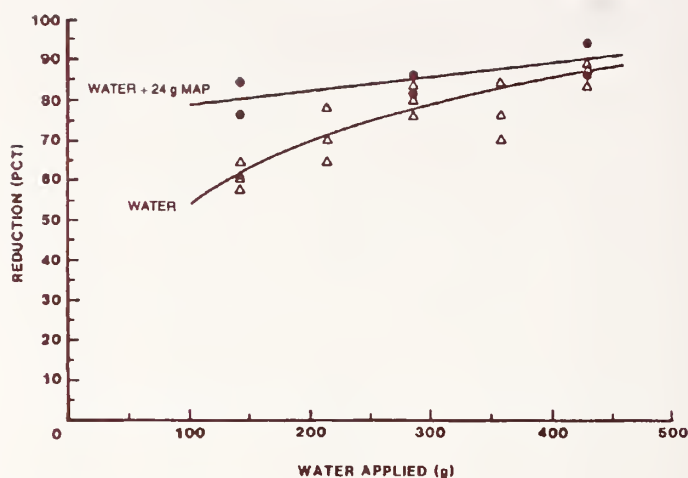


Figure 8—Combustion recovery energy release rate for water, and for water plus MAP.

### Maximum Combustion Recovery Magnitude—

Even though SS2 indicates the sustained  $E_R$  level, the maximum recovery magnitude is also a good measure of how water and chemicals affect energy release. The magnitude to which combustion recovers for the last time before the fuels burn out was measured at point I. Figure 8 shows the reduction in  $E_R$  that was reached. The maximum  $E_R$  at point I was reduced 62 percent when the burning fuel was sprayed with 144 g of water. Adding 24 g MAP caused an additional reduction of 18.3 percent. Doubling the water improved the reduction by water alone by 15.9 percent. Adding 24 g MAP to the 288 g water reduced the  $E_R$  by 85.2 percent. Tripling the water to 432 g increased the reduction 25.2 percent over the basic 144 g water. Twenty-four grams MAP in 432 g water improved the reduction by only 2.8 percent.

Figure 9 plots the times from when the sprayer was turned off until the maximum  $E_R$  of SS2 was reached relative to the amount of water and chemical applied to the fire. It shows the elapsed times before the fires were reduced to their lowest intensity and then recovered to the highest energy release rates since treatment was ended. Table 4 lists the  $E_R$  and time data derived from the weight loss and irradiation traces. When 144 g water was sprayed onto the burning pine needles, the maximum recovery occurred in 1.7 minutes. Adding 24 g MAP increased the time of recovery 2½-fold. Doubling the water increased the time to 5.02 minutes, and adding 24 g MAP increased the time 61 percent. Spraying 432 g water increased the time to 8.35 minutes, slightly longer than half as much water with MAP added. Adding 24 g MAP increased the time to 12.35 minutes or about 50 percent.

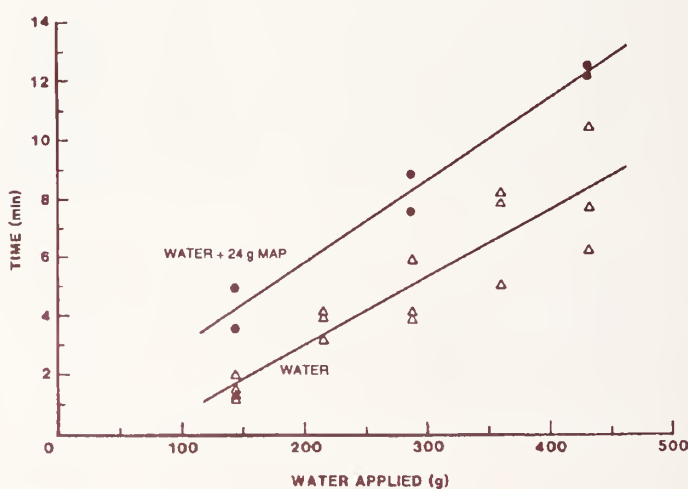


Figure 9—Time to maximum combustion recovery for water, and for water plus MAP.

## CONCLUSIONS

### Energy Release Reduction

Figure 10 shows a summary of the differences caused by treatments on the energy release rates measured during combustion recovery at the BC, SS1, and SS2 trace segments. Table 5 lists the treatments and the resultant

percentage decreases in energy release rates for the three parameters and the differences between effects of water and water plus 24 grams MAP. These data were derived from plots in figures 2, 3, and 5.

The “knockdown” capabilities of the treatments are indicated by their effects on the energy release rate decrease measured at trace segment BC. The BC span of change with increases of 144 to 432 g water + 24 g MAP is 11.8 percent. The BC span of difference in water and water plus MAP is only 0.4 percent (11.4 to 11.8)—meaning very little or no change with increasing penetration and decreasing chemical in each droplet. This indicates that increasing penetration and decreasing concentration make very little difference in fire “knockdown.” This would indicate that the “knockdown” is most effective at the surface of the fuel and the chemical involved is of little consequence at that time, or that the effects of the quantity of water overshadow the effects of the decreasing amounts of chemical in each droplet. As a rule of thumb, we can say that water alone, for the amounts applied in

**Table 4—Combustion recovery energy release rate data**

Fire	Water	MAP	I	I reduction	IT-NT
	---- g ----		Btu/s	Percent	Min
M28N1	144	0	102.7	61.6	1.22
M28N2	144	0	112.0	58.2	1.53
M28N3	144	0	96.4	60.9	2.00
M28N4	144	0	96.4	65.2	1.37
JUN11N2	144	24	48.2	84.7	4.97
JUN11N3	144	24	51.5	76.8	3.60
JUN8N1	216	0	83.4	70.4	3.20
JUN8N2	216	0	86.7	65.0	3.95
JUN8N3	216	0	51.5	78.7	4.15
JUN9N1	288	0	48.2	80.6	4.15
JUN9N2	288	0	41.8	84.1	3.90
JUN9N3	288	0	54.5	76.5	5.93
JUN11N4	288	24	38.5	82.2	8.85
JUN11N5	288	24	32.1	86.3	7.57
JUN9N4	360	0	32.2	84.7	5.05
JUN9N5	360	0	73.8	70.5	7.88
JUN9N6	360	0	57.8	76.7	8.23
JUN4N1	432	0	28.9	89.2	10.45
JUN4N2	432	0	29.5	87.8	7.73
JUN10N1	432	0	41.8	83.8	6.25
JUN11N6	432	24	16.0	94.1	12.23
JUN11N7	432	24	32.2	86.9	12.55

<sup>1</sup>Is the 6 second average of  $E_p$  at the highest recovery rate; IT and NT are the elapsed times for points I and N to occur.



**Figure 10—Energy release comparisons—BC (knockdown), SS1 (holddown), and SS2 (recovery).**

this study, decreased the energy release rate by 70 to 81 percent and the addition of 24 g MAP caused only an additional 7 percent decrease (table 5).

The fire “holddown” abilities of the treatments are indicated (fig. 10 and table 5) by the decreases in energy release rates and extended times measured for trace segment SS1. The SS1 span of change with increases of 144 to 432 g water is 13.3 percent but only 2.7 percent for increases of 144 to 432 g water plus 24 g MAP. This 10.6 percent difference indicates a moderate improvement with increasing penetration and decreasing chemical in each droplet. It appears that increasing penetration has a very positive effect on “holddown” and the chemical has a lesser effect. Keeping the fire intensity at a reduced level

**Table 5—Summary of Energy Release Rate Reductions and Durations**

Water applied	Energy release rate			
	Water only		Water + 24g MAP	
	reduction	duration	reduction	duration
<i>g</i>	<i>Percent</i>	<i>Min</i>	<i>Percent</i>	<i>Min</i>
<b>BC</b>				
144	69.5	0.17	76.3	0.17
216	72.0	.17	78.9	.17
288	74.4	.17	81.7	.17
360	77.7	.17	84.8	.17
432	80.9	.17	88.1	.17
<b>SS1</b>				
144	79.1	0.56	91.4	2.03
216	85.7	1.31	91.9	3.37
288	89.1	2.41	92.6	4.82
360	91.1	3.86	93.4	6.37
432	92.4	5.68	94.1	8.12
<b>SS2</b>				
144	66.1	0.85	82.3	2.32
216	74.1	1.22	86.6	2.65
288	79.8	1.76	89.6	3.05
360	84.3	2.54	92.0	3.50
432	87.9	3.67	93.9	4.02

for a longer time appears to be accomplished more effectively by the higher water volumes and by the higher solution concentrations. The retardant chemicals cause increased effectiveness for the low water volumes, much more than for the higher water volumes.

**SS2 Magnitude**—The magnitude to which the energy release rate returns after most of the water and chemical have been lost is measured by the SS2 segment of the weight trace. The span of change with increases of 144 to 432 g water is a 21.8 percent decrease in the maximum energy release rate. SS2 span of change with increases of 144 to 432 g water plus 24 g MAP is 11.6 percent. The span of differences between water and water plus MAP is 10.2 percent. As with SS1, SS2 shows a moderate change with increasing penetration and decreasing chemical in each droplet. The differences between water only and water plus MAP treatments show that there are definite advantages to the use of chemicals at all levels of treatment, with the least amount of water showing the most significant advantage.

**SS1 Duration**—The time periods that SS1 and SS2 burn are also indicative of the effects of treatments on burning fuels (table 5). The duration of SS1 (holddown) increased by 10 times when the water-only treatment was tripled from 144 to 432 g. With the MAP solution, the duration increased fourfold for 144 and 432 g water. The time between water and water plus MAP less than doubled from 1.47 to 2.46 minutes at the 432 g level. These data show that the time that the fire intensity was subdued increased by fourfold at the high-chemical-concentration, low-penetration applications, and increased by less than 50 percent at the low-concentration, high-penetration applications.



**SS2 Duration**—The duration of SS2 (table 5) increased fourfold when the water only treatment was tripled from 144 to 432 g. For the MAP solution the duration increased by less than twice when the water treatment was tripled. The span of difference between water and water plus MAP decreased less than fourfold from 1.47 to 0.35 minutes difference at the 432 g level. Adding MAP at the high water treatment levels does not appear to extend the SS2 duration significantly.

## Combustion Recovery

**Time Until Start**—The delay of the start of the buildup to maximum recovery (during SS1) showed that adding MAP to the water prolonged the low energy output rate. By increasing the water treatment by three times, the delay increased by about sixfold, and by adding 24 grams MAP the delay was increased by 273 percent at the lowest water treatment and by only 56 percent at the highest water treatment. The decrease in added effectiveness caused by MAP was again overshadowed by the increases in water quantity, but at all levels the MAP did add to the delaying effect.

**Time to Maximum**—The total elapsed time for the burning fuel to be held at a low  $E_R$  and then build to its maximum was prolonged by the addition of MAP. Water alone delayed the peak  $E_R$  to 1.7 minutes with a 144-g water-only treatment, and to 8.35 minutes (491 percent increase) with a 432-g treatment. Adding MAP to the water increased the delay by 249 percent at the 144-g water level, and only by 148 percent at the 432-g level.

**Maximum Magnitude**—The addition of MAP to water showed an advantage in decreasing the maximum  $E_R$  during the last recovery when the water and MAP were probably at their minimum quantities on the fuel bed. When 144 g water was applied, the maximum  $E_R$  was reduced by 62 percent over the maximum when there was no treatment. Adding 24 g MAP reduced the maximum another 18.3 percent. At the higher water treatment levels, the addition of the MAP made a smaller difference but still caused significant reductions in the  $E_R$ , that is, 432 g water reduced  $E_R$  87.2 percent and the MAP improved that by only 2.8 percent.

## MANAGEMENT APPLICATION

Whether or not a retardant is a short-term (depends solely on water to reduce combustion) or long-term (depends on chemical and water to reduce combustion), the most important consideration is capability to reduce energy release rate. Another important factor is how long the retardant can hold the combustion below an intensity that will support fire spread through treated fuels and thus on into untreated fuels. The data in this study show that the MAP used in currently approved forest fire

retardants does increase the capability of water to reduce fire intensity and delay combustion recovery when the retardant is applied directly on the flames. The use of chemical causes the most improvement when used at the highest concentrations or when water is in short supply. As the amount of water increases, the difference between the effectiveness of water alone and water plus chemical decreases to a level where the effect of water quantity overshadows the effects of the chemical.

The objective of this study was to determine if water/chemical mixtures were superior to ordinary water if applied directly to flames of active fires. The data in this study show that there is a significant advantage to using chemicals. The capability of water to immediately reduce flames to smoldering combustion is enhanced only slightly by retardant chemicals. But the chemical significantly reduced fire intensity and extended the times that the flames were reduced as smoldering continued. Chemical retardant can be a definite advantage during direct attack fire suppression efforts.

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# APPENDIX A: WEIGHT AND IRRADIATION TRACES FOR FIRES TREATED WITH WATER AND MONO-AMMONIUM PHOSPHATE

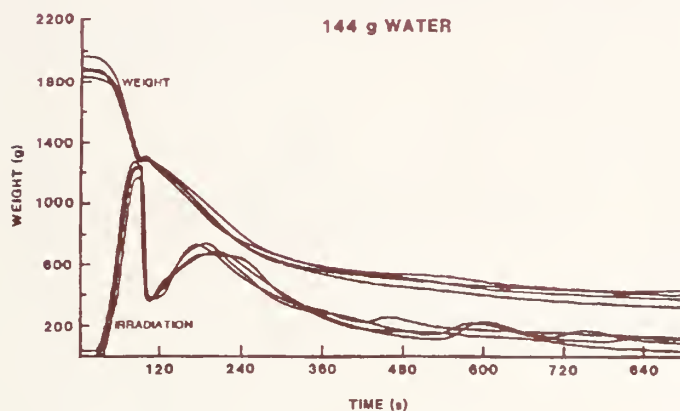


Figure 11—Treatment: 144 g water.

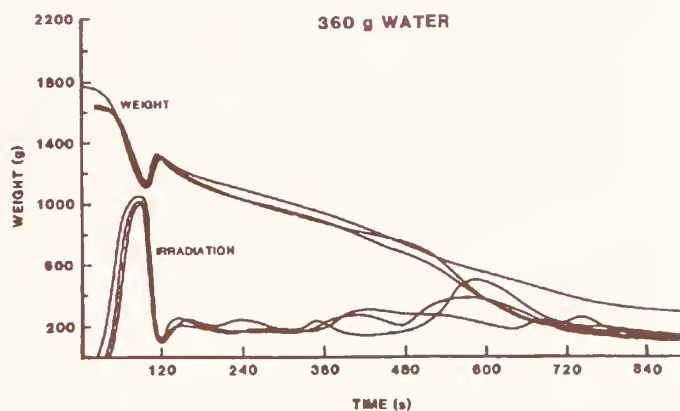


Figure 14—Treatment: 360 g water.

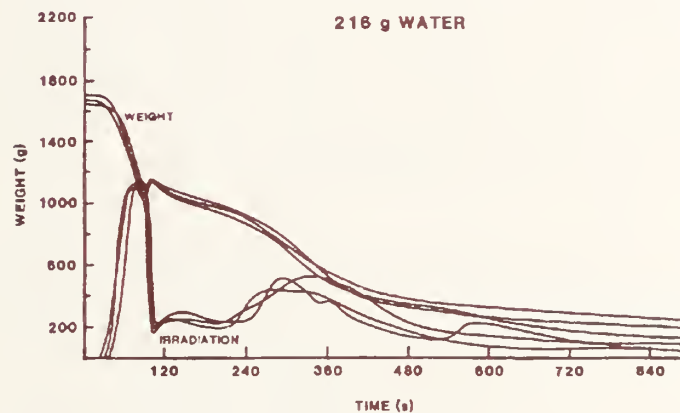


Figure 12—Treatment: 216 g water.

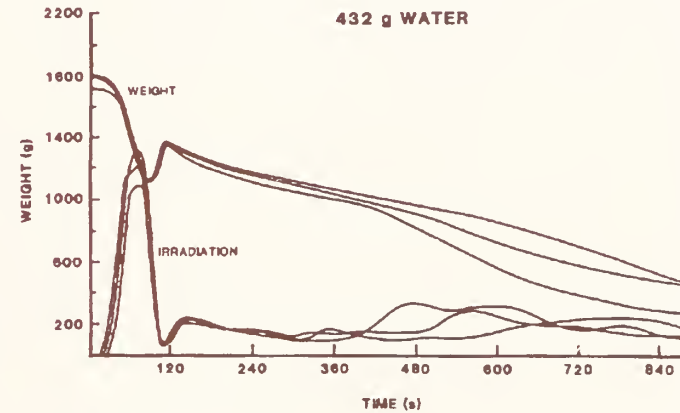


Figure 15—Treatment: 432 g water.

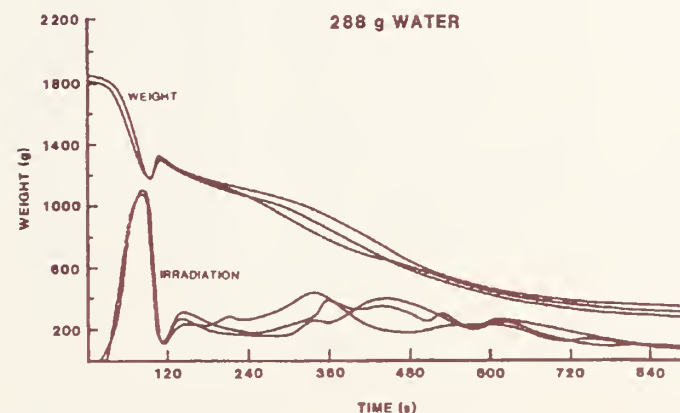


Figure 13—Treatment: 288 g water.

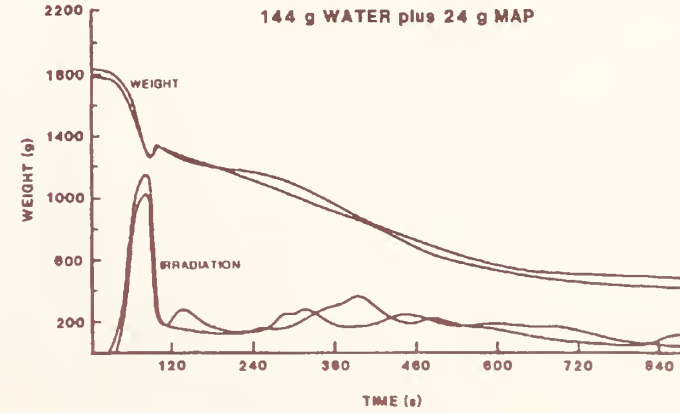


Figure 16—Treatment: 144 g water plus 24 g mono-ammonium phosphate.

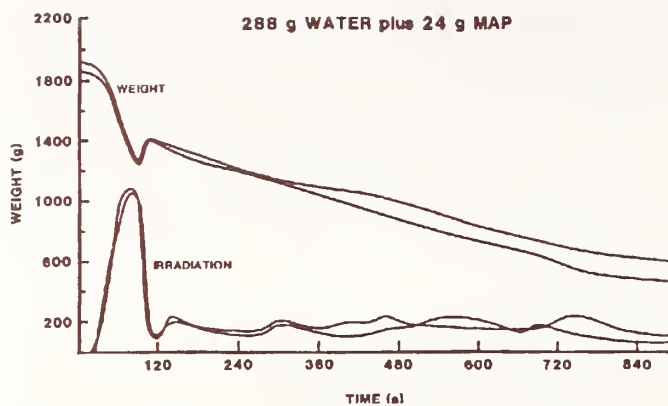


Figure 17—Treatment: 288 g water plus 24 g mono-ammonium phosphate.

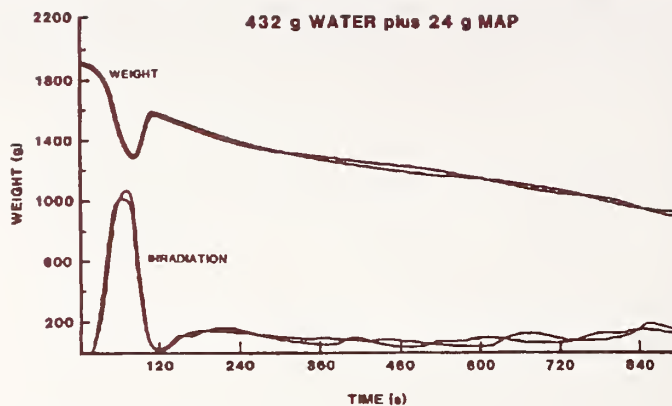


Figure 18—Treatment: 432 g water plus 24 g mono-ammonium phosphate.

## APPENDIX B: WEIGHT AND TIMES FROM DESIGNATED POINTS ON WEIGHT TRACES

Table 6—Weight and times from designated points on weight traces<sup>1</sup>

Fire	Water/MAP	A	AT	B	BT	C	CT	D	DT	E	ET
	<i>g/g</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>
M28N1	144.00	1,164	92	1,139	108	1,073	129	385	440	363	462
M28N2	144.00	1,288	89	1,263	104	1,204	123	425	545	396	575
M28N3	144.00	1,237	82	1,233	97	1,175	120	473	543	444	580
M28N4	144.00	1,245	81	1,157	101	1,087	124			873	177
JUN11N2	144.24	1,300	81	1,296	105	1,234	129	1,161	228	1,193	249
JUN11N3	144.24	1,362	74	1,373	94	1,347	106	1,245	183		
JUN8N1	216.00	1,186	160	1,226	179	1,153	201	998	302		
JUN8N2	216.00	1,109	81	1,135	105	1,095	119	978	208		
JUN8N3	216.00	1,241	80	1,263	99	1,212	116	1,091	202		
JUN9N1	288.00	1,245	82	1,303	111	1,208	138	1,044	252		
JUN9N2	288.00	1,157	96	1,237	121	1,168	148	1,091	189	1,047	214
JUN9N3	288.00	1,186	78	1,245	106	1,172	132	989	279		
JUN11N4	288.24	1,336	80	1,380	114	1,307	140	1,139	277	1,195	303
JUN11N5	288.24	1,267	85	1,347	113	1,263	143	1,128	267	1,084	304
JUN9N4	360.00	1,131	92	1,289	120	1,237	138	987	321	1,069	260
JUN9N5	360.00	1,241	68	1,395	97	1,285	133	919	384		
JUN9N6	360.00	1,219	71	1,373	98	1,281	122	1,000	306	861	394
JUN4N1	432.00	1,274	69	1,354	112	1,281	143	1,091	331	1,055	353
JUN4N2	432.00	1,212	77	1,358	117	1,278	145	1,080	314		
JUN10N1	432.00	1,263	76	1,442	109	1,351	135	1,124	321		
JUN11N6	432.24	1,314	73	1,567	115	1,384	220	1,201	514	1,131	602
JUN11N7	432.24	1,296	74	1,493	120	1,398	172	1,051	623	996	676

<sup>1</sup>A, B, C . . . weight taken at points on the weight trace; AT, BT, CT . . . times on the irradiation trace corresponding to points on the weight trace.

Table 7—Weight and times from designated points on weight traces<sup>1</sup>

Fire	Water/MAP	F	FT	G	GT	H	HT	I	IT	J	JT
	<i>g/g</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>
M28N1	144.00	1,139	108	1,073	129			853	177	780	193
M28N2	144.00	1,263	104	1,204	123	1,036	165	883	191	671	238
M28N3	144.00	1,233	97	1,175	120	1,022	165	817	212	747	231
M28N4	144.00	1,157	101	1,087	124	937	164	873	177	594	245
JUN11N2	144.24	1,113	280	996	339	959	356	861	393	681	500
JUN11N3	144.24	1,157	253	1,142	258	1,109	273	1,044	302	747	465
JUN8N1	216.00	967	321	945	330			813	367	590	436
JUN8N2	216.00	970	216	953	225	886	257	616	337	422	398
JUN8N3	216.00	1,065	222	1,055	225	923	273	725	344	532	450
JUN9N1	288.00	1,018	273	883	345	897	339	853	354	671	434
JUN9N2	288.00	1,011	234	1,062	205	809	323	740	349	645	398
JUN9N3	288.00	970	298	828	379	718	421	619	457	531	495
JUN11N4	288.24	1,018	376	890	457	985	400	703	636	605	707
JUN11N5	288.24	1,007	419	901	521	886	531	846	559	671	693
JUN9N4	360.00	945	355	934	367	879	394	831	419	638	533
JUN9N5	360.00	839	461	758	500	645	533	502	566	374	614
JUN9N6	360.00	762	463	747	471	616	527	418	589	356	617
JUN4N1	432.00	908	547	700	715	674	733	674	733	487	858
JUN4N2	432.00	872	511	839	532	813	542	755	576	703	613
JUN10N1	432.00	1,047	401	981	439	912	468	890	478	579	637
JUN11N6	432.24	1,051	732	1,003	774	992	787	948	837	927	865
JUN11N7	432.24	934	787	868	850			850	862	809	898

<sup>1</sup>A, B, C . . . weight taken at points on the weight trace; AT, BT, CT . . . times on the irradiation trace corresponding to points on the weight trace.



Table 8—Weight and times from designated points on weight traces<sup>1</sup>

Fire	Water/MAP	K	KT	L	LT	M	MT	N	NT	O	OT
	<i>g/g</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>	<i>g</i>	<i>s</i>
M28N1	144.00	546	275	1,172	92	1,380	77	1,153	104	1,720	23
M28N2	144.00	641	269	1,311	87	1,464	76	1,292	99	1,819	24
M28N3	144.00	612	284	1,270	81	1,449	67	1,252	92	1,815	25
M28N4	144.00	535	273	1,204	83	1,391	70	1,183	95	1,829	19
JUN11N2	144.24	733	475	1,300	81	1,496	69	1,325	95	1,808	22
JUN11N3	144.24	977	346	1,362	74	1,523	60	1,391	86	1,830	21
JUN8N1	216.00	535	463	1,237	157	1,442	143	1,245	175	1,742	
JUN8N2	216.00	338	467	1,087	83	1,267	69	1,146	100	1,669	
JUN8N3	216.00	575	415	1,270	77	1,471	61	1,281	95	1,833	
JUN9N1	288.00	605	469	1,245	82	1,490	63	1,312	105	1,797	
JUN9N2	288.00	623	417	1,197	92	1,442	74	1,252	115	1,768	
JUN9N3	288.00	480	527	1,186	78	1,391	61	1,259	101	1,738	
JUN11N4	288.24			1,311	82	1,479	67	1,395	105	1,848	15
JUN11N5	288.24	769	605	1,292	82	1,438	70	1,362	105	1,870	18
JUN9N4	360.00	524	624	1,172	87	1,336	72	1,296	116	1,756	
JUN9N5	360.00	305	676	1,274	64	1,417	53	1,402	93	1,735	
JUN9N6	360.00	308	654	1,267	67	1,460	52	1,380	95	1,700	
JUN4N1	432.00	484	859	1,226	73	1,449	57	1,362	106	1,786	18
JUN4N2	432.00	696	617	1,212	77	1,413	61	1,362	112	1,793	18
JUN10N1	432.00	539	664	1,318	70	1,519	55	1,446	103	1,793	24
JUN11N6	432.24	916	883	1,380	67	1,563	54	1,581	103	1,881	12
JUN11N7	432.24	824	884	1,321	72	1,512	57	1,512	109	1,819	20

<sup>1</sup>A, B, C . . . weight taken at points on the weight trace; AT, BT, CT . . . times on the irradiation trace corresponding to points on the weight trace.

## APPENDIX C: EQUATIONS FOR ENERGY RELEASE RATES AND DURATIONS

### Data Plot Equations

BC Equations					
Figure	Plot parameters	Equations	Constants		R <sup>2</sup>
2.	% reduction vs. water vs. water/MAP	Y = 1/(A+BX)	A = 0.0154	B = −7.049E−6	0.798
		Y = 1/(A+BX)	A = 0.0140	B = −6.091	.912
SS1 Equations					
Figure	Plot parameters	Equations	Constants		R <sup>2</sup>
3.	% reduction vs. water vs. water/MAP	Y = A+B/X	A = 99.050	B = −2.882	0.811
		Y = A+BX	A = 89.733	B = 0.010	.270
4.	duration vs. water vs. water/MAP	Y = A*X <sup>B</sup>	A = 1.5E−5	B = 2.116	.846
		Y = A*X <sup>B</sup>	A = 8.5E−3	B = 1.123	.976
SS2 Equations					
Figure	Plot parameters	Equations	Constants		R <sup>2</sup>
5.	% reduction vs. water vs. water/MAP	Y = A+B*log X	A = −32.836	B = 19.898	0.902
		Y = A+B*log X	A = 29.702	B = 10.583	.929
6.	duration vs. water vs. water/MAP	Y = A*EXP(BX)	A = 0.407	B = 5.08E−3	.830
		Y = A*EXP(BX)	A = 1.535	B = 2.26E−3	.391
7.	sprayer off until start of SS2 time vs. water time vs. water/MAP	Y = A+BX	A = −1.821	B = 0.020	.868
		Y = A+BX	A = −0.878	B = 0.027	.946
Combustion Recovery Equations					
Figure	Plot parameters	Equations	Constants		R <sup>2</sup>
8.	% reduction vs. water vs. water/MAP	Y = A+B*LOGX	A = −52.122	B = 22.962	0.853
		Y = A+BX	A = 75.417	B = 0.033	.583
9.	water vs. time water/MAP vs. time	Y = A+BX	A = −1.630	B = 0.023	.824
		Y = A+BX	A = 0.190	B = 0.028	.973





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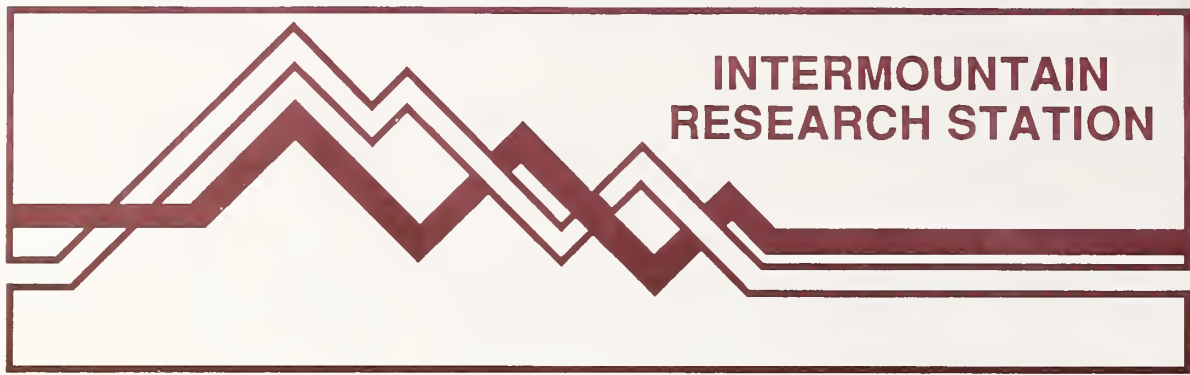
Blakely, Aylmer D. 1990. Combustion recovery of flaming pine needle fuel beds sprayed with water/MAP mixtures. Res. Pap. INT-421. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 15 p.

Water alone was the principal agent reducing flaming combustion to smoldering combustion; adding chemical retardant contributed only a slight additional reduction. Water alone was significantly less effective than chemical mixtures in reducing final energy release rates and maintaining reduced rates of fires allowed to recover. Data suggest that water/chemical mixtures are superior to water for extinguishing wildland fire.

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**KEYWORDS:** fire retardant, extinguish, energy release rate, fire behavior, fire management

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